Abstract

The III-Nitride semiconductor-based devices are showing their capability to fulfill the various technological demands generated from continuously changing electronic markets for the last three decades. Devices such as AlGaN/GaN High Electron Mobility Transistor (HEMT) have wide bandgap energy, large breakdown electric field, and high thermal stability, which make it a promising candidate for various technological areas, including consumer electronics, sensors to military and space applications. The continuous research in the GaN technology needs an understanding of theoretical fundamentals for the AlGaN/GaN HEMT analysis along with the knowledge and environment for epitaxial wafer growth and microfabrication facilities, which can further lead to developing these devices for the particular application. In order to do this, the Thesis was divided into different parts where the understanding of the AlGaN/GaN HEMT technology was developed by performing device simulation using their material properties along with the device physics. Further, the research work is extended to the epitaxial growth of AlGaN/GaN HEMT over Si (111) substrate and its characterization, which continuous towards different microfabrication process to develop the AlGaN/GaN HEMT devices for heavy metal ion sensing applications.

In the initial phase of this thesis work, the simulation studies on the AlGaN/GaN HEMT is carried out using the Sentaurus TCAD simulator tool by utilizing various device models to calculate energy bandgap, mobility, piezoelectric polarization, and surface traps of the AlGaN/GaN HEMT device. Subsequently, the simulated results are validated with experimental results by observing a correlation between the simulated and experimental electrical characteristics. Hence, mobility, surface trap concentration, and contact resistance were obtained as ~1270 $cm^2/V.s$, ~2×10^{13} cm^{-2}, and ~0.2 Ω.mm, respectively by simulation. Moreover, the impact of the self-heating on the electrical characteristics also observed, and it was found that at higher voltages, the generated electric field increases the lattice temperature in the device, which ultimately reduces the electron mobility and drain current.

AlGaN/GaN HEMTs also demonstrated their utility in the different chemical sensing applications due to the availability of surface traps and two-dimensional electron gas (2DEG) at the heterointerface, closed to the device surface. Thus, any surface change easily reflects on the 2DEG. In addition, the availability of 2DEG makes the device normally-on, which makes the sensor a reference electrode free device. Considering these advantages of the AlGaN/GaN HEMT, their fabrication was carried out in the next phase of this research work for heavy metal ion sensing applications. Herein, the epitaxial growth of the AlGaN/GaN HEMT structure was carried out on Si (111) substrate by metal-organic chemical vapor deposition (MOCVD) approach and corresponding material characterizations such as X-ray diffraction (XRD), atomic force microscopy (AFM), and transition electron microscopy (TEM) were also performed. These characterizations show excellent epitaxial growth of the AlGaN/GaN HEMT structure. Moreover, the electrical characterizations such as the transmission line measurement (TLM) process were also performed to determine the contact and sheet resistance of the developed AlGaN/GaN structure. These wafers were further utilized for the development of AlGaN/GaN HEMT based heavy metal ion sensors using different microfabrication processes.

Heavy metal ions, including Mercury (Hg^{2+}), Lead (Pb^{2+}), and Cadmium (Cd^{2+}), are very toxic and hazardous to human health even at trace level concentration in water. Thus, there is a requirement for an accurate, reliable, and rapid technique for the detection of heavy metal ions. In this regard, the AlGaN/GaN HEMTs were developed as sensors to detect these toxic heavy metal ions. Thus, extensive work has been carried out to demonstrate the novel AlGaN/GaN HEMT based Cd^{2+} ion sensor with Mercaptopropionic Acid (MPA) and Glutathione (GSH) functionalization. The sensing response of the developed sensor was observed by detecting Cd^{2+}

ions at different concentrations. The AlGaN/GaN HEMT sensor exhibits excellent response with the sensitivity of 0.241 μA/ppb, a fast response time of ~ 3 seconds, and a lower detection limit of 0.255 ppb. The observed lower detection limit is significantly lower than the World Health Organization (WHO) standard guideline values for Cd^{2+} ions in drinking water. Furthermore, the sensor showed good selectivity of Cd^{2+} ions towards other toxic heavy metal ions. The results indicate that the binding properties of GSH to Cd and the sensitivity of 2DEG towards the variation of charges at the gate region make the device highly sensitive with the rapid detection of Cd^{2+} ions.

By observing the exciting results after the development of AlGaN/GaN HEMT as a sensor for the detection of Cd^{2+} ions, we developed the AlGaN/GaN HEMT based sensor for sensitive and selective determination of Pb^{2+} ions. Here, the gate region of the HEMT was functionalized by 2,5-di-mercapto-1,3,4-thiadiazole (DMTD). The sensor's response is observed by monitoring drain to source current (I_{DS}) for different concentrations of Pb^{2+} ions at a fixed drain to source voltage (V_{DS}). The developed sensor reaches the lower detection limit of 0.018 ppb, which is much lower than the WHO's standard limits for drinking water. Furthermore, the sensor exhibited a rapid response time of ~ 4 seconds and high sensitivity of 0.607 μA/ppb. Moreover, the selectivity analysis was performed and found that the sensor was highly selective towards Pb^{2+} ions. The change in electron concentration at 2DEG upon the capture of Pb^{2+} ions at the gate region by DMTD causes a change in the I_{DS}, which showed excellent sensing response towards Pb^{2+} ions. The highly sensitive, selective, and rapid detection of Pb^{2+} ions paves the way for stable sensing performance based on DMTD functionalized AlGaN/GaN HEMT sensor.

Since mercury is a highly toxic pollutant and causes several environmental and health-related issues throughout the world, therefore, it is necessary to develop a sensor for highly sensitive, selective, and rapid determination of the trace amount of toxic Hg^{2+} ions. In this research work, the detection of trace concentrations Hg^{2+} ions was investigated by the development of molybdenum disulfide (MoS_2) functionalized AlGaN/GaN HEMT. The vertically aligned, flower-like MoS_2 structures are synthesized through a simple hydrothermal process and applied to the au gated region of AlGaN/GaN HEMT. The scanning electron microscopy (SEM), Raman spectroscopy, and XRD are performed for the structural characterization of MoS_2. Further, Hg^{2+} ions' sensing is performed by electrical characterizations of MoS_2 functionalized AlGaN/GaN HEMT. The sensor showed an excellent sensitivity of 0.64 μA/ppb and a detection limit of 0.01152 ppb with a rapid response time of 1.8 s. The sensor exhibits the linear range of detection from 0.1 ppb to 100 ppb and highly selective behavior towards Hg^{2+} ions. The results demonstrated that the MoS_2 possesses excellent Hg^{2+} ions capture property, which could be attributed to the complexation of Hg^{2+} ions with sulfur and the electrostatic interaction between MoS_2 and Hg^{2+} ions alter the I_{DS} of the AlGaN/GaN HEMT at a constant V_{DS}. Therefore, the AlGaN/GaN HEMT devices with different functionalizing materials possess a huge potential for next-generation ion sensing applications.

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